THIS IS ONE VOLUME OF A SIX VOLUME SET WHICH INCLUDES:

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Category 2	Organization:	Environmental Management

TITLE:
AQUIFER PUMPING TESTS

Approved By: [signature] MAY 12, 1992
(Name of Approver) (Date)

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2.0 PURPOSE AND SCOPE

This standard operating procedure (SOP) discusses equipment and procedures that will be used at the Rocky Flats Plant (RFP) to conduct aquifer pumping tests in driven well points and/or drilled and completed wells. This SOP addresses "step-drawdown" and "constant rate discharge" pumping tests, and is based upon information contained in references presented in Section 4.0.

An aquifer pumping test is an *in situ* test used to assess hydraulic characteristics representative of the aquifer being tested. This is accomplished by stressing a subject aquifer through the removal or addition of water and measuring hydrostatic pressure response. Typically, a production well is pumped at fractions of full capacity with pumping rates changing in a time step fashion, "step-drawdown", and/or at a constant rate, with water levels measured at frequent intervals in the production well and one or more observation wells (Walton, 1987). Time-drawdown and distance-drawdown data are recorded and used to calculate aquifer characteristics through type-curve matching, straight-line matching or inflection-point techniques.

3.0 PERSONNEL QUALIFICATIONS

Personnel conducting the aquifer pumping test will be geologists and/or engineers with backgrounds in hydrology, or field technicians with an appropriate amount of applicable experience or on-the-job training under the supervision of other qualified personnel.

4.0 REFERENCES

4.1 SOURCE REFERENCES

The following is a list of references reviewed prior to the writing of this procedure:

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U. S. Environmental Protection Agency (EPA), Ground Water Handbook, Office of Research and Development, EPA/625/6-87/016, March 1987, 212 p.

Walton, W. C., 1962, Selected Analytical Methods for Well and Aquifer Evaluation. State of Illinois Department of Registration and Education, Bulletin 49, p. 6.

Walton, W. C., 1970, Groundwater Resource Evaluation. McGraw-Hill Book Co., New York, 664 p.

Walton, W. C., 1987, Groundwater Pumping Tests. National Water Well Association, Lewis Publishers, Inc., Chelsea, Michigan, 201 p.

4.2 INTERNAL REFERENCES

Related SOPs cross-referenced by this SOP are as follows:

- SOP FO.3, General Equipment Decontamination
- SOP FO.5, Handling of Purge and Development Water
- SOP FO.7, Handling of Decontamination Water and Wash Water

- SOP FO.15, Photoionization Detectors (PIDs) and Flame Ionization Detectors (FIDs)
- SOP GT.6, Monitoring Wells and Piezometer Installation
- SOP GW.1, Water Level Measurements in Wells and Piezometers
- SOP GW.2, Well Development
- SOP GW.3, Pump-In Borehole Packer Testing
- SOP GW.5, Field Measurement of Groundwater Field Parameters
- SOP GW.6, Groundwater Sampling

5.0 EQUIPMENT AND PROCEDURES

5.1 EQUIPMENT

Aquifer pumping tests will be conducted using an arrangement of equipment that will satisfy the requirements specific to the test conditions. The following is a general list of equipment needed to perform aquifer pumping tests:

- A reliable power source
- Submersible or suction pump (pumping rates may range from 0.01 gpm to 10 gpm)
- Flow meter
- Borehole flow meter (optional)
- Discharge control equipment
- Water discharge line
- Temporary holding tank
- Pressure transducers
- Data loggers
- Electronic water level indicator

- Timeclock or watch with second hand or digital readout of seconds
- Field notebook and/or field forms

Specific equipment and materials requirements will vary with the type of aquifer pumping test being performed.

Guidelines presented in SOP FO.3, General Equipment Decontamination, are to be followed for decontaminating equipment involved in aquifer pumping tests.

5.2 WELL INSTALLATION AND DEVELOPMENT

All wells should be installed per guidelines in SOP GT.6, Monitoring Wells and Piezometer Installation, except for specific design requirements as set forth in this SOP. Newly installed wells will be checked for the presence of an immiscible layer prior to well development. The method for detecting these layers in monitoring wells is discussed in SOP GW.1, Water Level Measurements in Wells and Piezometers. If an immiscible layer of 5 mm or greater is detected in a newly installed well, well development procedures will not continue until the EG&G Project Manager has been notified. In the case where an immiscible layer is not identified, a water level measurement will be taken according to SOP GW.1 and well development activities will continue. The water level measurement along with the total well depth measurement will be used to determine the volume of water in the well casing. Well casing calculations are presented in Section 5.2.11 of SOP GW.1.

5.2.1 Determination of Aquifer Pumping Test Well Location

When selecting a site for an aquifer pumping test, consideration will be given to the characteristics of the site as it relates to possible potentiometric surface fluctuations as a result of nearby surface loading (traffic, etc.), and to the expected gradient of the water table.

5.2.2 Aquifer Pumping Test Well Installation

All pumping wells will be fully penetrating. The heterogeneity of the alluvial materials, Arapahoe Formation, and Laramie Formation at the RFP require that the well screen be strategically placed.

5.2.2.1 Well Type

Drilled wells will be constructed according to SOP GT.6, Monitoring Wells and Piezometer Installation and will have a six-inch to one-foot sump of unscreened casing at the bottom of the well. The base of the well casing will be capped. Driven well points may be used for shallow aquifer pumping tests and will be developed according to specifications set forth in this SOP. Driven wells may be installed in soft formations free of cobbles and boulders (Harlan and others, 1989).

5.2.2.2 Well Diameter

The well casing diameter will be as small as possible reducing the volume of water in the well, yet large enough to accommodate pumping and measuring equipment.

5.2.2.3 Filter Pack Construction

In wells drilled specifically for aquifer pumping tests, filter pack construction will follow the procedures outlined in SOP GT.6, Monitoring Wells and Piezometer Installation.

5.2.3 Aquifer Pumping and Observation Well Development

Well development is the process of removing drilling fluids, sediment and smeared or built-up materials from the borehole walls, filter packs, and/or well screens. It also is a process whereby fines within the formation adjacent to the borehole can be removed, thus enhancing well efficiency and allowing the inflow of physically and chemically representative ground water from the formation adjacent to the screened interval of the well. This process will be used for all observation and pumping wells, whether they are old wells or newly installed wells.

5.2.3.1 Materials and Equipment

The following is a list of well development and associated equipment:

- Mechanical reel equipped with a steel cable
  Submersible or suction pump, pump cables and hoses
- Water quality test kit (pH, SC, T)
- Wash/Rinse tubs
- Clear plastic sheeting
- Disposable latex or vinyl gloves
- Non-phosphate, lab-grade detergent (e.g., Liquinox)
- Containers for development water (see SOP FO.5, Handling of Purge and Development Water)
- Water level probe - sufficiently accurate to measure water levels to the nearest 0.01 foot
- Distilled Water
- Field notebook and/or field forms
- Health and safety equipment
- Organic vapor detector (OVD)
- Calculator

5.2.3.2 Well Development Procedures for Pumping and Observation Wells

Well development for new pumping test wells will be conducted no sooner than 48 hours and no longer than two weeks after installation. All aquifer pumping and observation wells, new and old, will be developed utilizing a vigorous development method known as backwashing. The pumping equipment of choice for well development, is a submersible or suction pump.

Backwashing involves alternatively turning a pump on and off to simulate a surging action in the well (EPA, 1987). Backwashing should be conducted at a pumping rate only slightly higher than the well can sustain to avoid clogging the well screen. If necessary, RFP tap water or formation water that has had the sediment removed, will be added to the well bore during the backwashing process to augment the volume of water depleted by periodic pumping to waste. The process of backwashing involves raising a column of water almost to the surface, shutting off the pump and allowing the water to fall back into the well. This process is repeated, starting and stopping the pump as rapidly as possible. To minimize the possibility of damaging the pump as a result of sediment-locking, the pump should initially be started at reduced capacity and gradually increased. The control box should be equipped with a starter lockout to avoid damage to the pump that may result when an attempt to start the pump is made while the pump is backspinning. During the backwashing procedure, the well should occasionally be pumped to waste to remove sediment brought into the water column by the surging action (Driscoll, 1986).

EG&G will determine whether a pump will be dedicated to a specific well based upon verified organic vapor detector (OVD) readings obtained during the drilling of the well. OVD readings are described in SOP FO.15, Photoionization Detectors (PIDs) and Flame Ionization Detectors (FIDs).

Development equipment will be protected from the ground surface with clear plastic sheeting. Development equipment will be decontaminated before well development begins and between well sites according to SOP FO.3, General Equipment Decontamination.

Decontamination and development water will be handled according to SOP FO.7, Handling of Decontamination Water and Wash Water, and SOP FO.5, Handling of Purge and Development Water, respectively.

5.2.3.3 Development Criteria

The criteria for adequate development of the well will be determined by the project hydrogeologist or engineer and will be approved by the EG&G Project Manager. Development criteria set forth in SOP GW.2, Well Development, Section 5.2.1, may be used as guidelines, but will not necessarily be binding. In addition, three consecutive well casing volume readings of pH, temperature, and specific conductance will be recorded (i.e., consecutive temperatures that are within 1°C, and pH readings that are within 0.2 units) and consecutive conductivity readings fall within 10 percent of each other. The calibration and use of these field instruments is described in SOP GW.5, Measurements of Groundwater Field Parameters.

5.3 PROCEDURES

The selection of an aquifer pumping test will be based upon the estimates of hydraulic parameters that are being assessed. A test will be selected that will give the desired information while minimizing the complexity and time required to conduct the test.

Detailed geologic and hydrogeologic information of the test area will be gathered and synthesized into the aquifer pumping test plan. The amount of time available for the test should be considered.

Prior to the beginning of any aquifer pumping test, the following must be assessed:

- Design of Test
- Desired Information

- Geologic Conditions
- Analytical Solution and Boundary Conditions

5.3.1 Aquifer Pumping Test Design

To increase the probability that a proposed test site and associated equipment will yield acceptable results, and to minimize uncertainties in data collection and analysis, the following pumping test design criteria must be evaluated, to the extent that available data allows:

- The diameter, depth, and position of all intervals open to the aquifer system, as well as total depth

- Radial distance and direction from the production well to each observation well and from any interfering boundary

- Radial distance and direction from any known boundaries to each observation well

- Depth to, thickness of, and areal and vertical limits of the aquifer system

- The order of magnitude of pertinent aquifer system hydraulic characteristics (Walton, 1987)

It is essential to the success of a pumping test at the RFP that the relatively low hydraulic conductivities expected to exist in the materials being tested, be considered in the design of the pumping test. The low hydraulic conductivities will affect all aspects of the test design, including radius of influence, observation well spacing, pumping rate, length of time to pump well bore storage, duration of the effects of delayed yield, etc. In addition, some formations may exist in both confined and unconfined conditions throughout the RFP site. It is likely, while conducting a pumping test on such formations at a site which has been characterized as existing under confined conditions, that heads may draw down in the pumping well below the top of the confining layer, causing a change to unconfined conditions. If this possibility is suspected, then the test initially should be designed with unconfined conditions in mind. If it is desirable to maintain confined conditions during the test, for example, to do away with the long times potentially required to overcome delayed yield effects and thereby shorten the time required to complete the test, then an injection pumping test should be considered.

The design for a pumping test should begin with the selection of hydraulic parameters that are believed to represent the material being tested. This assessment will be obtained from laboratory analyses performed on soil and rock samples representative of the aquifer, or by packer tests conducted at or near the proposed test site. The design also may be guided by the results of a pretest single hole aquifer test. Drawdown in the pumping well will not exceed 20 percent of the saturated thickness if the aquifer is unconfined and will not go below the top of the aquifer if the aquifer is confined.

The Thiem equation can be used to determine the pumping rate as follows:

Unconfined aquifer:

$$Q = \frac{(K\pi)(2Hs-s^2)}{\ln (R/r_w)}$$

where:	R	=	radius of influence, (a large number, usually greater than 1000 feet, see Bear, 1979), (L),
	r_w	=	radius of the well (L),
	H	=	initial head (L),
	s	=	drawdown in the pumping well (L),
	K	=	hydraulic conductivity (L/T), and
	Q	=	pumping rate (L^3/T).

Confined aquifer:

$$Q = \frac{2\pi Kms}{\ln(R/r_w)}$$

where: m = thickness of the aquifer

This may be repeated for a range of hydraulic conductivities to establish a range of possible pumping rates. The pumping rates can then be used to design the spacing of the observation wells from the pumping well by assuming various values of r (distance between observation well and the pumping well) and solving for values of s. This process can be repeated using various pumping rates. The results can then be plotted with r versus s for various values of Q. From this graph the optimum pumping rate and observation well spacing can be chosen based on an acceptable minimum drawdown observable in the observation well most distant from the pumping well. It is recommended that the minimum observed drawdown for an observation well be at least 0.1 foot.

The effects of well bore storage can be significant in low hydraulic conductivity materials. To determine the time after pumping begins beyond which well bore storage impacts are negligible, the following equation can be used (Walton, 1987):

$$t_s = 5.4 \times 10^5 (r_w^2 - r_c^2)/T$$

where:

where:	t_s	=	time beyond which effects of storage are negligible (less than 1 percent of drawdown values)(min),
	r_w	=	production well effective radius (ft),
	r_c	=	pump-column pipe radius (ft), and
	T	=	transmissivity (gpd/ft).

At least three observation wells should be installed in the same aquifer as the pumping well and at various distances and directions from the pumping well. Observation well spacing will be logarithmic and designed to provide at least one logarithmic cycle of distance-drawdown data (Walton, 1987).

In the event that boundary conditions prevail, observation wells should be spaced along a line through the production well and parallel to the boundary to minimize the effects of the boundary on distance-drawdown data. If boundaries are of interest, it is desirable to space observation wells on a line perpendicular to the boundary and at variable distances and directions from the image well associated with the boundary (Walton, 1987).

The open, or screened portions of both the production and observation wells should be open to the same interval of the aquifer unless leaky conditions are anticipated. Where leaky conditions are anticipated, at least one aquifer observation well will be open to the same interval of the aquifer as the production well, and one aquitard observation well should be open to the lower portion of the aquitard. Where possible these wells will be fully penetrating.

In order to determine the appropriate duration for running a pumping test under water table conditions, one of the following equations should be used:

$$t_d = 5.4 \times 10^4 m S_y / P_h \text{ (Walton, 1962)}$$

where:	t_d	=	time after pumping started beyond which delayed gravity yield impacts are negligible (min),
	m	=	aquifer thickness (ft),
	P_h	=	aquifer horizontal hydraulic conductivity (gpd/ft^2), and
	S_y	=	aquifer water table storativity (specific yield) (dimensionless);

or,

$$t_i = 5.4 \times 10^3 (r_i^2) S_{aw} / T \text{ (Walton, 1987)}$$

where:	t_i	=	pumping test duration which must be exceeded if boundary impacts are to be clear (one logarithmic time cycle after impacts become appreciable) (min),

r_i = distance from observation well to boundary image well (ft),
S_{aw} = aquifer water table storativity (specific yield) (dimensionless), and
T = aquifer transmissivity (gpd/ft).

The equation which gives the greater duration is the equation that should be used.

Time intervals for observation well water level measurements vary from short at the start of the test, when water levels decline rapidly, to long at the end of the test, when the time rate of drawdown is small. A typical range of time intervals for observation well, water level measurements are shown in Table GW.8-1.

TABLE GW.8-1

TIME INTERVALS FOR TIME-DRAWDOWN DATA COLLECTION

Time After Pumping Started	Time Intervals
1 - 2 minutes	10 seconds
2 - 5 minutes	30 seconds
5 - 15 minutes	1 minute
15 - 50 minutes	5 minutes
50 - 100 minutes	10 minutes
100 - 500 minutes	30 minutes
500 - 1000 minutes	1 hour
1000 -5000 minutes	4 hours
5000 - end	1 day

5.3.2 Step-Drawdown Tests

A step-drawdown test (Driscoll, 1986) is used to assess well performance under conditions of turbulent flow. Also, the data obtained from a step-drawdown test can be used to determine the specific capacity of a well. This information can be used to select the optimum pumping rate and pump-setting depth for a constant-rate discharge test. Transmissivity and storativity values for the aquifer can be assessed from time-drawdown and distance-drawdown graphs plotted from data for the first step, and/or for any other step together with data for the preceding steps (Birsoy and Summers, 1980).

Once the pump has been installed in the production well, and the discharge control equipment, flow meter, pressure transducers, and other previously mentioned equipment have been installed, static water levels at each of the production and observation wells will be collected and recorded. After this has been performed, the data logger will be programmed, pre-test water level data recording initiated, and the test is ready to begin.

During a step-drawdown test, the production well will be pumped at several successively higher pumping rates during which time-drawdown data will be collected for each rate, or step. Generally, a step-drawdown test should be completed within one day, however, in materials of low hydraulic conductivity, effects due to well bore storage may significantly increase the time required to complete the test. The pumping times for each step of the test will be the same (approximately 0.5 to 2 hours in duration) in order to simplify calculations. During the performance of these tests, between three and eight pumping steps will be used.

Electronic pressure transducers and a data logger will be installed in the production well and the observation wells to record time-drawdown data during both the pumping and recovery phases of the test. In addition, hand measurements will be collected as backup data. In addition to collection of time-drawdown data, flow rate data also will be collected. The information collected during the duration of this test will be recorded on the data sheet provided in Appendix GW.8A.

5.3.3 Constant-Rate Discharge Tests

A constant-rate discharge test, with one or more observation wells, can be used to assess the drawdowns in a well at future times and different discharges, the radius of the cone of influence for individual or multiple wells, as well as the transmissivity and storativity of the aquifer. The pumping rate to be maintained for the duration of the test, the pump-setting depth, and the test duration will be determined prior to commencement of a constant-rate discharge test.

Once the pump has been installed in the production well, the discharge control equipment, flow meter, pressure transducers, and other previously mentioned equipment are installed, static water levels at each of the production and observation wells will be collected and recorded. After this has been performed, the data logger will be programmed, pre-test water level data recording initiated, and the test is ready to begin.

The pump being utilized for the pumping test will begin pumping at a previously determined time. In order to simplify calculations, the time in which the test commences should be on a ten-minute interval. The data logger will be set to begin collecting data just before or at the same time the pump begins pumping. Once the pumping test begins, hand collected time-drawdown measurements will begin. These measurements should begin at the production well and continue at the observation wells in a pattern that will allow for the most rapid collection of data from well to well. The time for collecting hand measurements should follow the times provided in Table 1 as closely as practicable.

During the pumping test, the flow meter will be monitored regularly to ensure that a constant flow rate is being maintained. In the event that a constant flow rate is not being maintained, adjustments to the pump, power source, or discharge control equipment may need to be performed. Flow rates will be monitored at regular time intervals throughout the duration of the test, with the time intervals being small at the beginning of the test. Records of flow rate versus time and time-drawdown data will be maintained throughout the duration of the test.

After completion of the pumping test, recovery data will be collected. The procedures for data collection during the recovery phase of the test will be identical to those preformed during the pumping phase of the test. The information collected during the duration of this test will be recorded on the data sheet provided in Appendix GW.8A.

5.4 METHODS OF ANALYSIS

For each aquifer pumping test, the analytical solution will be consistent with the conditions at the test site, the information desired, and the test design. The project hydrogeologist will be responsible for choosing the analytical method and interpreting the test results. The methods used may include those presented in the published literature presented in Section 4.0

Analytical solutions of pumping test results are based upon the type of flow encountered during the test and the type of aquifer being tested. This section will first discuss analytical methods for analyzing pumping test data with steady-state flow conditions, and followed by transient analytical solutions. These solutions are further subdivided according to aquifer type.

5.4.1 Steady-State Solutions

5.4.1.1 <u>Confined/Unconfined Aquifers</u>

The most widely used solution is based upon the Thiem equation (Lohman, 1979). Two different forms of the Thiem equation are available. One is to be used for confined aquifers and one for unconfined aquifers. If the aquifer is unconfined, the drawdown should be adjusted using the Jacob (1963) method (Walton, 1970):

$$s_a = s_{wt} - (s_{wt})^2/2m$$

where:

where:	s_a	=	drawdown that would occur in an equivalent non-leaky confined aquifer (ft),
	s_{wt}	=	observed drawdown under water table conditions (ft), and
	m	=	initial saturated thickness of the aquifer (ft).

5.4.2 Transient Solutions

Because transient analytical solutions consider aquifer storage, the analytical solutions can yield values for specific yield or storativity.

5.4.2.1 Confined Non-Leaky Aquifers

Transmissivity and storativity can be determined with the Theis (1935) solution using data drawn from plots of drawdown versus time on log-log paper. Curve matching techniques with a type-curve (available in Lohman, 1979) render values of time (T), dimensionless time (u), drawdown (s), and dimensionless drawdown [W(u), well function of u] which are then used to solve for values of hydraulic parameters. Assumptions for the use of this solution are as follows (Lohman, 1979):

- The aquifer is homogeneous and isotropic;
- The aquifer is infinite in areal extent;
- Water is released from storage instantaneously with decline in head;

- The aquifer is of uniform thickness over the area influenced by the aquifer test;
- The discharging/injecting well maintains a constant discharge rate;
- The discharging/injecting well is fully penetrating; and
- The potentiometric/phreatic surface is horizontal prior to pumping.

Corrections are available to compensate for violations of some of these assumptions (Kruseman and De Ridder, 1983), including corrections for partial penetration, barometric pressure fluctuations, and well-bore storage.

The Theis method also can be applied to analyzing recovery data (Jacob, 1963). The solution is derived by using image well theory and superimposing an injection well upon a discharging well. A semi-log plot of draw-down versus t/t' (where t = time since pumping began and t' = time since recovery began) yields a straight line through the origin (assuming storage is the same for pumping and recovery). Transmissivity is determined from the slope of the line (Kruseman and De Ridder, 1983).

If the value for dimensionless time, u, is less than or equal to approximately 0.01, the Cooper and Jacob (1946) straight line method is valid. A semi-log plot of drawdown versus time yields a straight line for later time values. The slope of the line and its extension to intercept with zero drawdown can be used to solve for transmissivity and storativity respectively.

If three or more observation wells have been installed at different directions from the pumping well, and the aquifer is of sufficient homogeneity, then directional hydraulic conductivity may be obtained from the analysis of the time-drawdown data. The directional hydraulic conductivity may be obtained by the method described by Papadopulos (1965).

5.4.2.2 Confined Leaky Aquifers

There are many solutions available for leaky confined aquifers (Kruseman and De Ridder, 1983). Lohman (1979) discusses the Hantush (1955) and Cooper (1963) method, which does not consider storage in the confining unit, and the Hantush (1960) method which does consider confining unit storage. Standard curve matching techniques are used to solve for transmissivity and storativity. If confining unit thickness is known, the Hantush-Jacob (1955) method will yield vertical hydraulic conductivity in the confining unit.

5.4.2.3 Unconfined Aquifers

Unconfined aquifers subjected to pumping go through three distinct phases (Freeze and Cherry, 1979). During early stages of pumping, the response of an unconfined aquifer will resemble that of a confined aquifer due to the expansion of water and compaction of the aquifer. The second phase shows the effect of gravity drainage. Time-drawdown curves will display a decreased slope due to the delayed yield response of unconfined aquifers. During the third phase, time-drawdown curves will again resemble the Theis-type curve.

The Theis type-curve may be used for early and late pumping test data. However, storage parameters calculated during the early stages of pumping tests may be in the range for that of confined aquifers and must not be used to predict long term drawdowns (Prickett, 1965). Boulton (1963) gives a curve that allows the estimation of the time at which gravity effects are negligible and the Theis type-curve may be used to match late pump test data. The storage parameter calculated with this later data can be used to predict long-term effects of aquifer pumping (Prickett, 1965).

Boulton (1963) and Prickett (1965) have developed methods of analyzing pumping test data subject to delayed yield. Families of delayed yield type-curves based upon Boulton's method are available in Lohman (1979) with which standard type-curve matching techniques are used.

5.4.2.4 Fractured Rock Aquifers

Available methods for interpreting pumping tests in fractured (fissured) aquifers have been summarized by Gringarten (1982). These pumping test analysis methods are usually based upon solutions for an "equivalent" porous media aquifer, which attempt to relate the actual fractured aquifer behavior to that of a known theoretical model, homogeneous or heterogeneous, of lower complexity. The double-porosity concept may be applicable to the types of fractured aquifers which may be encountered at the RFP. This concept is a possible analysis tool for fractured aquifers. In double-porosity aquifers, the fractures and rock matrix blocks form a dual system for transmitting water, with the fractures having a high hydraulic conductivity and low storativity and the rock matrix having a low hydraulic conductivity and high storativity.

Both confined and unconfined type-curve models may be used to analyze pumping test data from fractured aquifers. For double-porosity analyses, the type curves given by Boulton (1963) for delayed yield are identical to those corresponding to the time-drawdown curves for a confined, double-porosity fractured rock aquifer (Gringarten, 1982) and may be used to analyze the fractured aquifer. In this case the fluid released from the fractures occurs first, with the fluid released from the rock matrix appearing as "delayed" yield.

5.4.2.5 Conclusions

For each pumping test performed, the analytical solution will be consistent with the conditions at the test site, the information desired, and the test design. The project hydrogeologist will be responsible for choosing the analytical method and interpreting the test results.

Many additional methods to analyze aquifer tests are available. It is recommended that more than one method be used to analyze each aquifer test. This will allow comparison of values for different methods since no two methods will yield the exact same results. To aid in analysis, several commonly used analytical methods have been outlined in Appendix GW.8B along with the references from which they were obtained. Methods that assume that an aquifer is confined may be used when analyzing unconfined aquifer test data; however, corrected drawdowns must be used (Jacob, 1963). A review of the reference should be made before analyzing the pumping test data.

6.0 DOCUMENTATION

Documentation for this SOP will include an aquifer pumping test approval form developed to aid in successful aquifer pumping test design. This form should be completed as a part of the procedure for developing an appropriate aquifer pumping test design and is attached as Appendix GW.8C. Once the aquifer pumping test approval form is completed, it must be reviewed approved by the EG&G Project Manager prior to the start of the aquifer pumping test.

APPENDIX GW.8A
AQUIFER PUMPING TEST DATA SHEET

AQUIFER PUMPING TEST DATA SHEET

DATE _________ PERSON RECORDING DATA __________________

WELL # _____________

HYDROSTRATIGRAPHIC UNIT _________________________

SCREENED INTERVAL ______ft to ______ft

STATIC WATER LEVEL ______ft PUMPING WELL I.D. __________in

DISTANCE TO PUMPING WELL _______ft

TEST START TIME _____:_____:____

ELAPSED TIME (Units)	WATER LEVEL (Units)	Q (pumping well) (Units)

.
.
.

etc.

AQUIFER PUMPING TEST ANALYSIS
THIEM STEADY STATE METHOD

WELL # ____________

HYDROSTRATIGRAPHIC UNIT ______________________

SCREENED INTERVAL ______ ft to ______ ft

Reference: Lohman (1979)

Assumptions:
- Those listed in reference
- Steady state flow

K = hydraulic conductivity (L/T)
T = transmissivity (L^2/T)
r_1 = distance from pumping well to monitoring well #1 (L)
r_2 = distance from pumping well to monitoring well #2 (L)
h_1 = water level in monitoring well #1 (L)
h_2 = water level in monitoring well #2 (L)
s_1 = drawdown in monitoring well #1 (L)
s_2 = drawdown in monitoring well #2 (L)
b = Aquifer thickness (L)

UNCONFINED AQUIFER:

Q = __________ (L^3/T)
r_1 = __________ (L) r_2 = __________ (L)
h_1 = __________ (L) h_2 = __________ (L)

$$K = \frac{-2.30 * Q * \log_{10}(r_2/r_1)}{\pi(h_2^2 - h_1^2)} = \_\_\_\_\_\_\_\_ \text{ (L/T)}$$

$T = K*b$ = ________________ (L^2/T)

CONFINED AQUIFER:

Q = ________ (L^3/T)
s_1 = ________ (L) s_2 = __________ (L)
r_1 = ________ (L) r_2 = __________ (L)

$$T = \frac{-2.30 * Q * \log_{10}(r_2/r_1)}{2\pi(s_1 - s_2)} = \_\_\_\_\_\_\_\_ \text{ } (L^2/T)$$

$K = T/b$ = __________________ (L/T)

AQUIFER PUMPING TEST ANALYSIS
THEIS CURVE MATCHING METHOD

WELL # ____________

HYDROSTRATIGRAPHIC UNIT ________________________

SCREENED INTERVAL ______ ft to ______ ft

Reference : Lohman (1979)

Assumptions:
- Those listed in reference
- Confined Non-Leaky Aquifer

s = drawdown in monitoring well (L)

t = time since pumping began (T)

r = distance from pumping well to monitoring well (L)

S = storativity (Dimensionless)

T = transmissivity (L^2/T)

u = dimensionless parameter = $r^2S/4*T*t$ (Dimensionless)

W(u) = Well function of u (Dimensionless)

MATCH POINT:

Q = __________ (L^3/T)

u = __________ (Dimensionless)

W(u) = ________ (Dimensionless)

t = _________ (T)

s = _________ (L)

T = $Q*W(u)/4\pi s$ = __________ (L^2/T)

S = $4*T*t*u/r^2$ = ___________ (Dimensionless)

AQUIFER PUMPING TEST ANALYSIS
THEIS RECOVERY METHOD

WELL # ____________

HYDROSTRATIGRAPHIC UNIT ______________________

SCREENED INTERVAL ______ft to ______ft

Reference: Kruseman and De Ridder (1983)

Assumptions:
- Those listed in reference
- Confined non-leaky aquifer
- Coefficient of storage is the same for pumping and recovery

s = drawdown in monitoring well (L)

t = time since pumping began (T)

t' = time since recovery began (T)

T = transmissivity (L^2/T)

ds = drawdown over one $\log_{10}$ cycle of t/t' (L)

Q = ____________________ (L^3/T)

T = 2.30*Q/4πds = __________ (L^2/T)

APPENDIX GW.8B
AQUIFER PUMPING TEST ANALYSIS FORMS

AQUIFER PUMPING TEST ANALYSIS
COOPER AND JACOB METHOD

WELL # ____________

HYDROSTRATIGRAPHIC UNIT ________________________

SCREENED INTERVAL ______ft to ______ft

Reference : Lohman (1979)

Assumptions:
- Those listed in reference
- $u \leq 0.01$
- Confined non-leaky aquifer

s = drawdown in monitoring well (L)

ds = change in drawdown for corresponding change in time (L)

t = time since pumping began (T)

dt = change in time for corresponding change in drawdown (T)

t_0 = time at which drawdown is 0 - from extrapolation of straight line through the X intercept (T)

r = distance from pumping well to monitoring well (L)

r_0 = distance from monitoring well at which drawdown is 0 - from extrapolation of straight line through the X intercept (L)

T = transmissivity (L^2/T)

S = storativity (Dimensionless)

u = dimensionless parameter = $r^2S/4*T*t$ (Dimensionless)

"r" IS CONSTANT:

Q = __________________ (L^3/T)

$T = \frac{2.30\,Q}{4\pi ds/d\log_{10}t}$ = ________ (L^2/T) $S = 2.25T(t/r^2)_0$ = __________ (Dimensionless)

Check $u \leq 0.01$ $u = r^2S/4*T*t$ = __________ (Dimensionless)

"t" IS CONSTANT:

Q = __________________ (L^3/T)

$T = \frac{-2.30\,Q}{2\pi ds/d\log_{10}r}$ = ________ (L^2/T) $S = 2.25T(t/r^2)_0$ = __________ (Dimensionless)

Check $u \leq 0.01$ $u = r^2S/4*T*t$ = __________ (Dimensionless)

AQUIFER PUMPING TEST ANALYSIS
COOPER METHOD FOR CONFINED LEAKY AQUIFERS

WELL # ____________
HYDROSTRATIGRAPHIC UNIT ________________________
SCREENED INTERVAL ______ft to ______ft

Reference: Lohman (1979)

Assumptions:
- Those listed in reference
- Confined leaky aquifer

s = drawdown in monitoring well (L)
t = time since pumping began (T)
r = distance from pumping well to monitoring well (L)
S = storativity (Dimensionless)
T = transmissivity (L^2/T)
K' = vertical hydraulic conductivity of confining unit (L/T)
b' = thickness of confining unit (L)
u = dimensionless parameter = $r^2S/4*T*t$ (Dimensionless)
v = dimensionless parameter = $r/2(K'/b'T)^{1/2}$ (Dimensionless)
$L(u,v)$ = Leakance function of u and v (Dimensionless)

MATCH POINT:

Q = ____________ (L^3/T)
u = ____________ (Dimensionless) t = ______________ (T)
$L(u,v)$ = __________ (Dimensionless) s = ______________ (L)
v = ____________ (Dimensionless)

T = $Q*L(u,v)/4\pi s$ = __________ (L^2/T)
S = $4T*t*u/r^2$ = ____________ (Dimensionless)
K' = $(4v^2b'*T/r^2$ = __________ (L/T)

APPENDIX GW.8C
AQUIFER PUMPING TEST APPROVAL FORM

APPENDIX GW.8C

AQUIFER PUMPING TEST APPROVAL FORM

PROJECT NO. ______________________ DATE ______________________

SUBCONTRACTOR ______________________

GEOLOGIST/ENGINEER ______________________

LOCATION ______________________

HYDROSTRATIGRAPHIC UNIT __________ TYPE OF AQUIFER __________

DESCRIPTION OF AQUIFER AND ITS SHAPE ______________________

____

ESTIMATED/ASSUMED HYDRAULIC PARAMETER DESIGN VALUES

K __________ (L/T) Source ______________________

K __________ (L/T) Source ______________________

S __________ (Dimensionless) Source ______________________

Q __________ (L^3/T) Source ______________________

Sat. Thickness __________ (L) Source ______________________

DEVELOPMENT METHOD ______________________

CRITERIA USED TO DETERMINE WELL IS DEVELOPED ADEQUATELY __________

	Reading 1	Reading 2	Reading 3
Temperature (°C)			
pH (std. units)			
Specific Conductance (uS/cm)			

ATTACH WELL COMPLETION DATA SHEET FOR PUMPING AND OBSERVATION WELLS.

PUMPING RATE ______________________ (L^3/T)

MAXIMUM DISTANCE OF OBSERVATION WELL (0.1 FT DRAWDOWN) __________ (L)

TIME AFTER WHICH AFFECT OF WELL BORE STORAGE IS NEGLIGIBLE __________ (T)

DURATION OF EFFECTS OF DELAYED YIELD __________ (T)

PARTIAL PENETRATION EFFECTS ______________________

SOLUTION METHOD ______________________

VIOLATIONS OF ASSUMPTIONS ______________________

OTHER ______________________

APPROVED ______________________

EG&G PROJECT MANAGER